DESIGN AND TESTING OF A MULTI-OUTPUT 300kV PROTOTYPE INDUCTION CELL PULSED POWER SUPPLY FOR DARHT

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ABSTRACT

Technology demonstrations of key components at LANL for the Dual-Axis Radiographic Hydro Test (DARHT) Facility including the turnkey Induction Cell Pulsed Power Supply (ICPPS) delivered by Maxwell have been in progress at the DARHT Integrated Test Stand (ITS) for over three years. The prototype system has accumulated >35,000 shots to date with no component failures and only minor system malfunctions. The eight induction cells in the ITS are driven by four water insulated Blumleins at 250 kV nominal, >67 ns wide negative polarity pulses with ±1% flat-top deviation. Each Blumlein drives two cells and is switched by an, SF_6 insulated, coaxial triggered spark gap. The Blumlein is charged using a pulse transformer via. two electrically isolated primary capacitors switched by their respective thyratrons. The timing adjustment between the respective Blumlein output pulses is controlled via Maxwell's turnkey DARHT HV Triggering System [1]. Four switching supplies provide independent control of each Blumlein output pulse voltage. The ICPPS prototype system is provided with a single integrated control console capable of remote operation via a MODICON programmable logic controller. Details of the ICPPS and the results obtained during this extensive testing are described.

INTRODUCTION

The turn-key system consists of four independent high voltage pulse forming sections. Each section, as shown in Figure 1, consists of a Blumlein and a charging unit (BCU) enclosure. All ancillary equipment associated with each BCU is located in a shielded enclosure outside the respective oil tank enclosure. The pulse voltage is injected into four cables (surge impedance 50 Ω each) at each Blumlein output. The controls for the BCUs and the four Maxwell CCDS high voltage switching power supplies (35 kV, 2 kJ/s) are located in two side-by-side 19 inch rack mount cabinets approximately 6 feet high, as shown in Figure 2. The control system is capable of selecting and operating any combination of the four BCUs located up to 100 feet away. Independent operation and monitoring of each of the four BCU/Blumlein can be performed either in the LOCAL mode from the control console front panels, or in the REMOTE mode via a MODICON programmable logic controller which interfaces to the ICPPS control system.

Each BCU oil enclosure assembly, shown in Figure 3, is 24 inches wide x 43 inches long x 41 inches deep. The BCUs utilize two independent 1.2 μF, 40 kV, capacitors which are discharged via two independent hollow anode glass thyratrons into two electrically isolated primary windings of a 1:11 step-up pulse transformer. This inverting pulse transformer charges the Blumlein intermediate conductor positively in ~4.5 μs. The spark gap is triggered close to the peak of the charge voltage waveform. When triggered the Blumlein injects a negative polarity pulse into the four matched output cables, each ~45 feet long.

Protection is provided for thyratron filament heater out-of-range voltage. A separate protection circuit monitors the pulse transformer reset current. The controls are provided with diagnostic circuits to detect a thyratron pre-fire condition. Furthermore, a thyratron overcurrent protection circuit is included to prevent operation if currents in excess of the thyratron rating are detected. The control system automatically disables and discharges the capacitors when a thyratron or the pulse transformer reset fault condition is detected. All interlocks are of the latching type and if breached are indicated both visually on the control console and relayed to REMOTE via a corresponding set of isolated relay contacts.

Each BCU enclosure is equipped with a single Pearson 110A current monitor to record the total primary (2 circuits) discharge current waveshape. Two independent resistive voltage dividers monitor the voltage pulse applied to the primary windings. The pulse transformer secondary voltage is, again, monitored via a resistive

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Technology demonstrations of key components at LANL for the Dual-Axis Radiographic Hydro Test (DARHT) Facility including the turnkey Induction Cell Pulsed Power Supply (ICPPS) delivered by Maxwell have been in progress at the DARHT Integrated Test Stand (ITS) for over three years. The prototype system has accumulated >35,000 shots to date with no component failures and only minor system malfunctions. The eight induction cells in the ITS are driven by four water insulated Blumleins at 250 kV nominal, >67 ns wide negative polarity pulses with ±1% flat-top deviation. Each Blumlein drives two cells and is switched by an, SF6 insulated, coaxial triggered spark gap. The Blumlein is charged using a pulse transformer via. two electrically isolated primary capacitors switched by their respective thyratrons. The timing adjustment between the respective Blumlein output pulses is controlled via Maxwell's turnkey DARHT HV Triggering System [1]. Four switching supplies provide independent control of each Blumlein output pulse voltage. The ICPPS prototype system is provided with a single integrated control console capable of remote operation via a MODICON programmable logic controller. Details of the ICPPS and the results obtained during this extensive testing are described.

15. SUBJECT TERMS

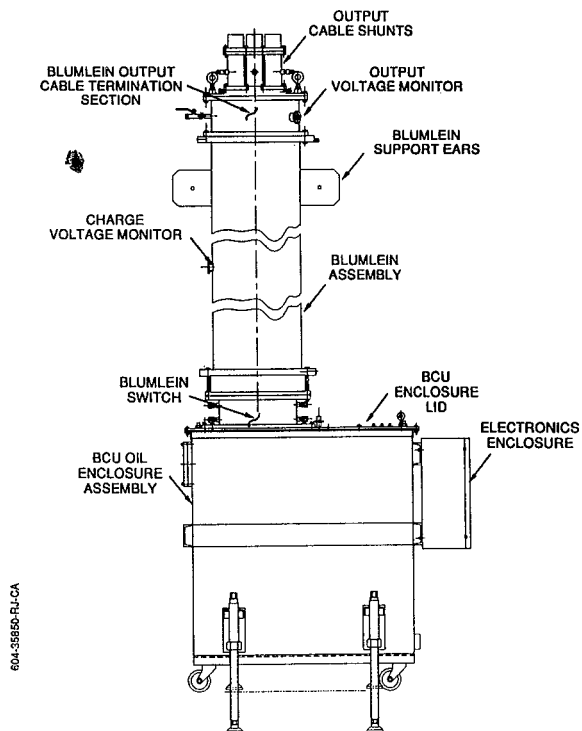| 16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**10**	

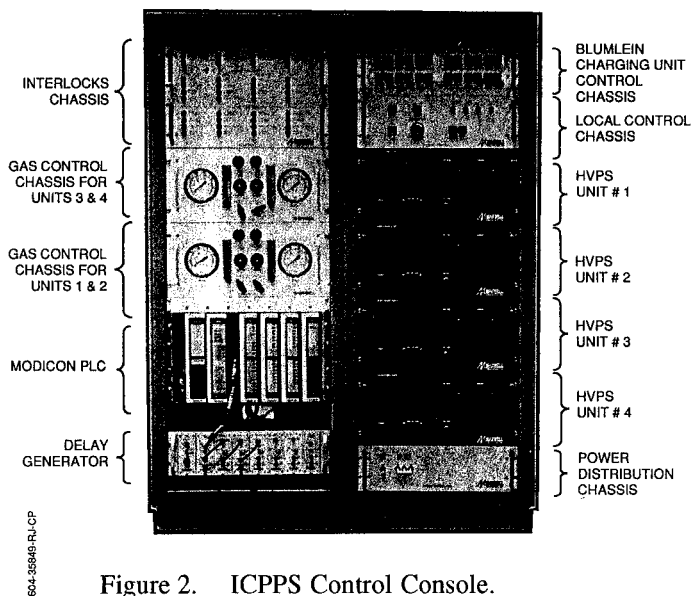Figure 1. A single Blumlein/BCU.

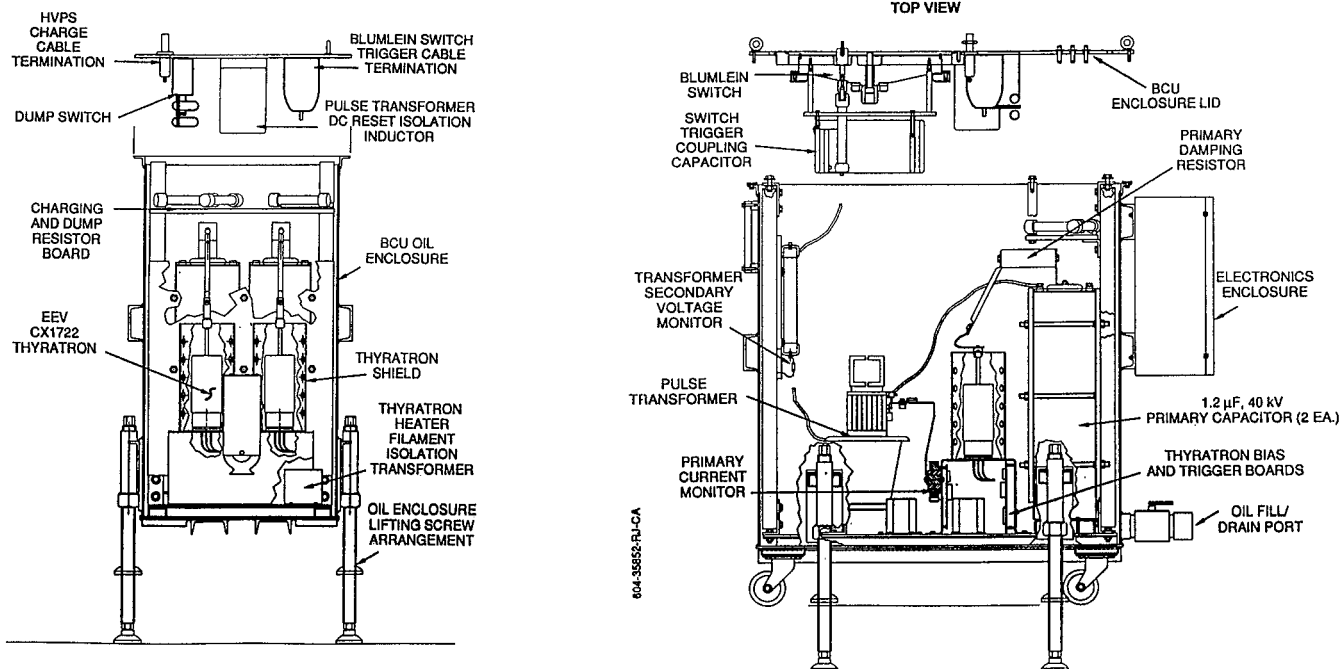Figure 2. ICPPS Control Console.

Figure 3. Blumlein Charging Unit showing component layout.

1413

voltage divider. This divider also provides the bias voltage for the Blumlein spark gap trigger electrode. A capacitive D-dot probe (~25 µs integrator) located in the middle of the Blumlein outermost conductor is used to monitor the intermediate conductor charge voltage, while a similar monitor at the Blumlein output is used for recording the pulse injected into the cables. The D-dot probe for output pulse employs special 50 Ω passive integrator with an integration time constant of ~1 µs. The voltage injected into each of the four cables connected at the output of the Blumlein is also measured via resistive cable shunts present around each of the output cables. These shunts, however, tend to be very noisy and require in-line high frequency (30 MHz) filter.

The ICPPS system can be operated either in a single shot mode or at low rep-rate (< 2 Hz). The 1-sigma jitter associated with the entire ICPPS system is <2 ns for any 100 shot test sequence at 0.2 Hz operation. All jitter measurements were made using a universal time interval counter (HP model 5370). No pre-fires or no-fires were present in a 5000 consecutive shot test at 0.2 Hz. Performance specifications for the DARHT Induction Cell Pulsed Power System, as demonstrated during the system acceptance testing, are outlined in Table I.

TABLE I
DARHT INDUCTION CELL PULSED POWER SUPPLY PERFORMANCE SPECIFICATIONS

Blumlein charge voltage	300 kV max.
Blumlein nominal operating range	100 kV to 275 kV
Blumlein charge polarity	Positive
Output pulse polarity	Negative
Blumlein charge time	< 4.5 µs
Reproducibility of charge voltage	$\leq \pm 1\%$ (3-sigma)
Output pulse flat-top width	> 67 ns (amplitude deviation ± 1%)
Pulse rep rate	0.2 Hz
Total system jitter (any 100 shot series) (from zero time trigger to HV output)	< 2 ns (1-sigma) < 10 ns total spread
Pre-fire and no-fire rate (@ 0.2 Hz)	None in 5,000 shots
Major component life	$> 10^7$ shots
BCU charge voltage (250 kV output)	29 kVmax. (10 MΩ-cm water)
Blumlein spark gap pressure/flow for 250 kV output pulse	48 psig, 500 cc/min.
Pulse leading edge risetime (10% to 90%)	≤ 18 ns

BLUMLEIN CHARGING UNIT ASSEMBLY

The electrical schematic of the transformer oil insulated BCU is shown in Figure 4. The shielded electronic enclosure housing the low voltage dc supplies for the thyratron trigger pulser, transformer reset supply, and the window comparator circuit boards is mounted on the outside of the steel enclosure. The following sub-components are present within the BCU steel enclosure:

Primary Capacitors: The capacitance in the BCU transformer primary circuit is matched to the Blumlein. Each of the two 6 Ω sections of the Blumlein, charged in parallel, present a total capacitance of ~20 nF which requires a matched total primary capacitance of 2.4 µF. Two 1.2 µF capacitors connected in parallel are used. This is done to reduce the primary circuit inductance, reduce the maximum current switched per thyratron, and ensure equal current sharing between the two thyratrons used in the primary circuit. No capacitor failures have been recorded to date. The specifications for the primary storage capacitors are given in Table II.

Thyratron Switch and Triggers: Hollow anode, deuterium-filled, glass envelope, tetrode thyratrons with high peak forward and reverse current capability are used. They can also handle very large rate-of-change of anode current and exhibit low jitter. The hollow anode structure enables the tube to cope with inverse voltage and currents without reduction (generally due to electrode damage) in its high voltage holdoff capability. Performance data for the thyratron is given in Table III.

1414

The thyratrons are powered via separate isolation filament transformers with the heater voltage maintained at ~6.4 V ac. The current drawn by each thyratron heater is ~24 A rms. A negative 130 V bias is provided for grid G2 while grid G1 of each thyratron is provided with ~150 mA priming current by a thyratron grid bias circuit, shown in Figure 5. This circuit board also monitors the thyratron filament ac voltage which is maintained within 6.0 V ac to 6.6 V ac. The thyratron is triggered by series injecting a trigger pulse in the grid G2 circuit as shown. A separate thyratron pulser board using an IGBT switch provides ~500 V trigger to the 1:4 pulse transformer. This pulser board provides two pulses in sync to trigger the two thyratrons simultaneously. With the BCU primary circuit charged to 1.5 kV, the thyratrons fired with a relative time delay ~133 ns with respect to each other. The jitter associated with this switching delay was determined to be ~2 ns (1-sigma) with a total spread of <8 ns.

With the BCU charged to 31 kV to deliver 275 kV nominal output pulse, each thyratron easily handled its peak discharge current of 10.5 kA. A typical current discharge pulse is shown in Figures 6 where the Blumlein switch is triggered close to the peak of the Blumlein charge voltage. The thyratrons survived the worst case 55% current reversals, which results when the Blumlein switch fails to trigger due to high gas pressure. To date the 8 thyratrons present in the ICPPS system have accumulated >35,000 shots each over 3 years of operation with discharge currents on the order of 9.8 kA peak.

<table>
<tr><th colspan="2">TABLE II
PRIMARY CAPACITOR SPECIFICATIONS</th><th colspan="2">TABLE III
THYRATRON SPECIFICATIONS</th></tr>
<tr><td>Model</td><td>Maxwell No. 36130</td><td>Model</td><td>EEV CX1722</td></tr>
<tr><td>Capacitance</td><td>1.2 µF</td><td>Cooling</td><td>Oil</td></tr>
<tr><td>Voltage rating</td><td>40 kV, oil insulated</td><td>Forward anode voltage</td><td>35 kV max.</td></tr>
<tr><td>Voltage reversal</td><td></td><td>Inverse anode voltage</td><td>25 kV max.</td></tr>
<tr><td>   Normal operation</td><td>20%</td><td>Forward current</td><td>16 kA max.</td></tr>
<tr><td>   Fault (1 in 1,000 shots)</td><td>87%</td><td>Reverse current</td><td>12 kA max.</td></tr>
<tr><td>Peak discharge current</td><td>20 kA</td><td>Average anode current</td><td>0.5 A</td></tr>
<tr><td>Discharge frequency</td><td>100 kHz</td><td>Rate-of-current rise</td><td>50 kA/µs</td></tr>
<tr><td>Rep-rate</td><td>2 Hz</td><td>Pulse rep-rate</td><td>100 pps</td></tr>
<tr><td>Self inductance</td><td>20 nH</td><td>Life</td><td>$>10^8$ Shots</td></tr>
<tr><td>Dielectric system</td><td>Hazy polypropylene,
MIPB insulated</td><td>Size</td><td>12in. H x 3.3in. OD</td></tr>
<tr><td></td><td></td><td>Jitter</td><td>1 to 5 ns</td></tr>
<tr><td>Life</td><td>$>10^7$ shots (99% survival)</td><td>(depending on type of</td><td></td></tr>
<tr><td>Size</td><td>7 in. W x 7 in. D x 26 in. H</td><td> ac or dc heaters and</td><td></td></tr>
<tr><td>Capacitors per BCU</td><td>2 each</td><td> triggering scheme)</td><td></td></tr>
</table>

Pulse Transformer: An iron core pulse transformer with a 1:11 step-up ratio is employed. The transformer, with two electrically isolated primary windings, inverts the pulse polarity output on the single secondary. To ensure reproducibility of the Blumlein charge voltage of better than ± 1 percent, a 40 A dc bias is applied to reset the transformer core. Reset is applied on the transformer primary winding via an isolation inductor, rated ~1 mH, 35 kV, to protect the low voltage (5 V dc) supply from the high voltage pulses. All pulse transformers have operated to date without any failure. The relevant specifications of the pulse transformer are given in Table IV.

<table>
<tr><th colspan="4">TABLE IV
PULSE TRANSFORMER SPECIFICATIONS</th></tr>
<tr><td>Model</td><td>Stangenes #SI-7672</td><td>Secondary voltage</td><td>300 kV</td></tr>
<tr><td>Type</td><td>2 winding, dual primary,
inverting</td><td>Reset current
Pulse duration</td><td>40 A @ 5V
5 µs half sine</td></tr>
<tr><td>Step-up ratio</td><td>1:11</td><td>Primary current</td><td>25 kA peak</td></tr>
<tr><td>Magnetizing inductance</td><td>>160 µH (referred to primary)</td><td>Secondary capacitance</td><td><150 pF</td></tr>
<tr><td>Leakage inductance</td><td><1 µH (referred to primary)</td><td>Isolation Inductor</td><td>1 mH, 35 kV</td></tr>
<tr><td>Primary voltage</td><td>35 kV</td><td></td><td></td></tr>
<tr><td>Secondary voltage</td><td>300 kV</td><td></td><td></td></tr>
</table>

A SINGLE BLUMLEIN CHARGING UNIT SHOWN
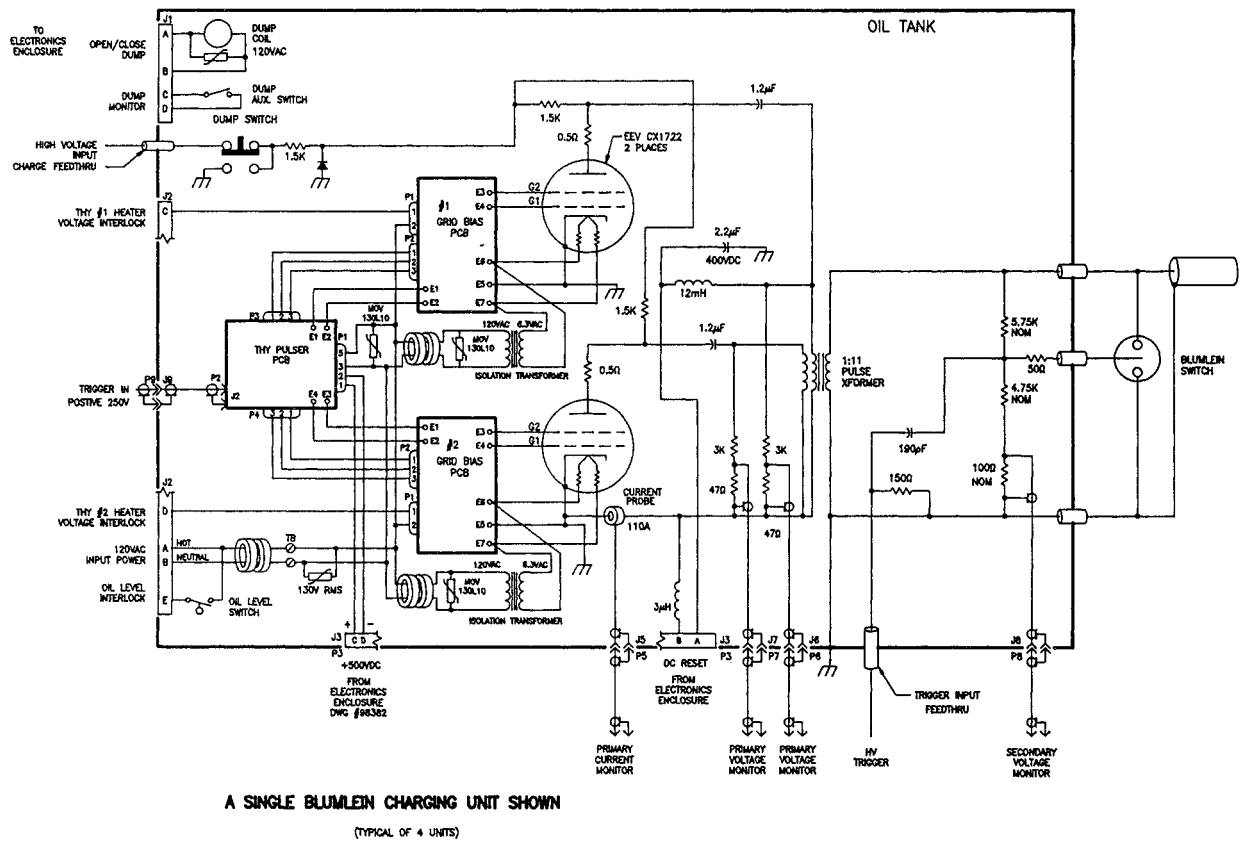
(TYPICAL OF 4 UNITS)

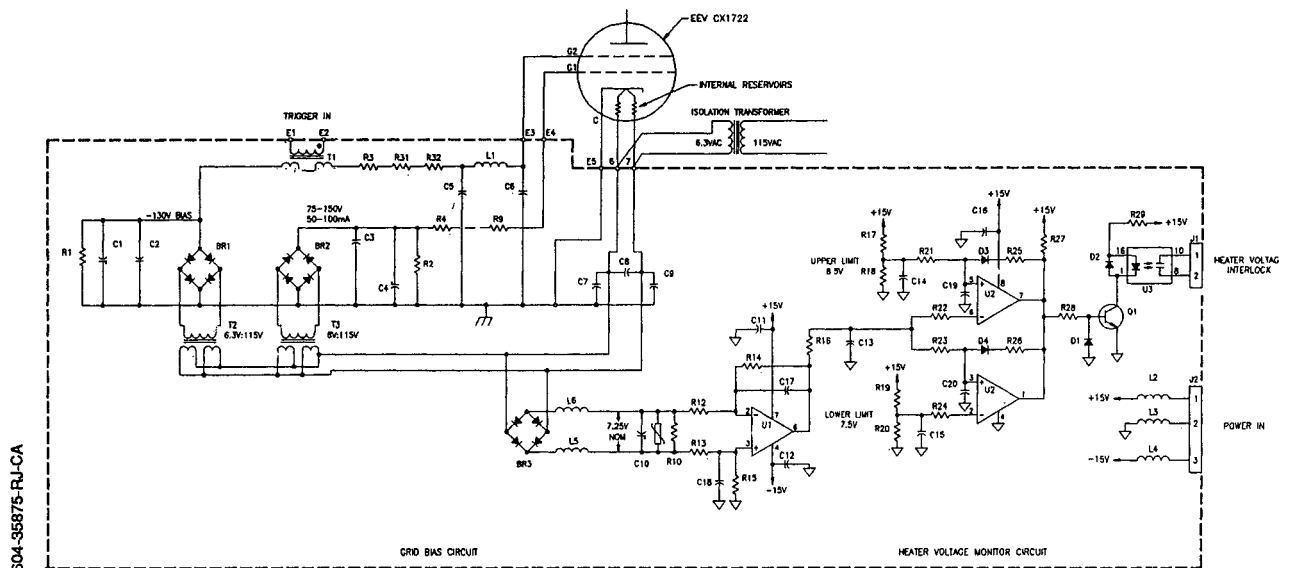Figure 4.   Electrical schematic for BCU oil enclosure.

Figure 5.   Thyratron biasing and trigger circuit schematic.

1416

BLUMLEIN PULSE FORMING SECTION

Blumlein Design: The 12 Ω Blumlein consists of three, concentrically placed, stainless steel coaxial cylinders as shown in Figure 7. The coaxially located cylinder volume is filled with deionized water which is continuously circulated through a deionizer to maintain the water resistivity at >10 MΩ-cm. The two concentrically placed coaxial lines forming the Blumlein are 6 Ω each with the ratio of the radii of the outer coaxial cylinder to the inner coaxial cylinder for the two halves being 2.45. The Blumlein outer ground conductor has an ID of ~15.6 inch and is ~80.5 inch long. The center conductor of the Blumlein is ~78 inch long and has an OD of ~2.5 inch. The intermediate conductor has an OD of ~6.5 inch, an ID of ~6 inch and is ~77 inch long.

Computer simulations using Maxwell's MAXCAP transient circuit analysis code and JASON field solving code were extensively used during the design of the Blumlein. Based on simulations an electrical length of 60 ns was required to deliver an output pulse with a 70 ns flat-top (± 1% deviation in pulse height at flat-top) to the four cables which are terminated into resistive-capacitive load of 12 Ω and 600 pF. The physical length of each Blumlein used in the ICPPS system was, thus, 80 inches nominally. The measured Blumlein output pulse into a matched resistive load, shown in Figure 8, validates the simulations.

The following equations (from Lupton and Eilberg at the Naval Research Laboratory) relating the breakdown field in water to the electrode area and the effective time of voltage stress were used:

$$F_- = 560\alpha t_{ef}^{-1/3} A^{-0.07}$$

Eq. 1

$$F_+ = 230 t_{ef}^{-1/3} A^{-0.06}$$

Eq. 2

The breakdown fields in transformer oil were calculated from the well known J.C. Martin's relationship given by:

$$E = 500 t_{ef}^{-1/3} A^{-0.1}$$

Eq. 3

where, F_- and F_+ are the water breakdown fields (in kV/cm) for negatively and positively charged electrodes respectively, E is the positive electrode oil breakdown field (in kV/cm), t_{ef} is the effective time (in μs) for which the applied electric stress exceeds 63% of the breakdown value, and A is the electrode area (in cm^2) under stress. The factor α is a correction factor which is applicable for widely divergent fields. The correction factor α, related to the peak and mean electric field, for a coaxial line with characteristic impedance Z is given by:

$$\alpha = 1 + 0.12 \left[60 \left(\frac{e^{Z\varepsilon^{0.5}/60} - 1}{Z\varepsilon^{0.5}} \right) - 1 \right]^{1/2}$$

Eq. 4

Hence for a 6 Ω water (ε = 81) coaxial line, the correction factor from Eq. 4 is found to be α = 1.09.

It is evident from the coefficients in Eq. 1 and Eq. 2, that a Blumlein charged positive and delivering a negative output pulse yields the most compact physical structure. It is important to note that the breakdown field depends on the area of electrodes under stress. At first glance, the area dependence does not appear to be a sensitive one as evident by the relatively weak power dependence. However, despite this relatively weak dependence, careful attention was given to assess the reliability issues of the overall system performance due to this dependence. A large number of ICPPS systems (up to 48 Blumleins) will be simultaneously used in the final DARHT facility and hence the area dependence on the high voltage integrity of large number of Blumleins cannot be ignored to yield a reliable and credible system design. In consideration of the reliable operation of the Blumleins, the design took into account the total number of Blumleins in the system to select the radial size of the Blumlein coaxial cylinders. This is important since, for a given electrical stress, the reliability tends to decrease as the number of elements in the system increase.

To select optimum Blumlein coaxial cylinder diameters, the ratio of operating to breakdown field strengths associated with various cylinder diameters were analyzed. When the operating-to-breakdown stress ratio is at or below 50%, the breakdown probability is very low. In this analysis, the predicted breakdown field strength for a single and four Blumleins was considered with Blumlein outer cylinder diameters varying in the range of 10 inches through 18 inches. Blumlein charge times of 3 μs, 5 μs, and 10 μs were investigated. The operating-to-breakdown
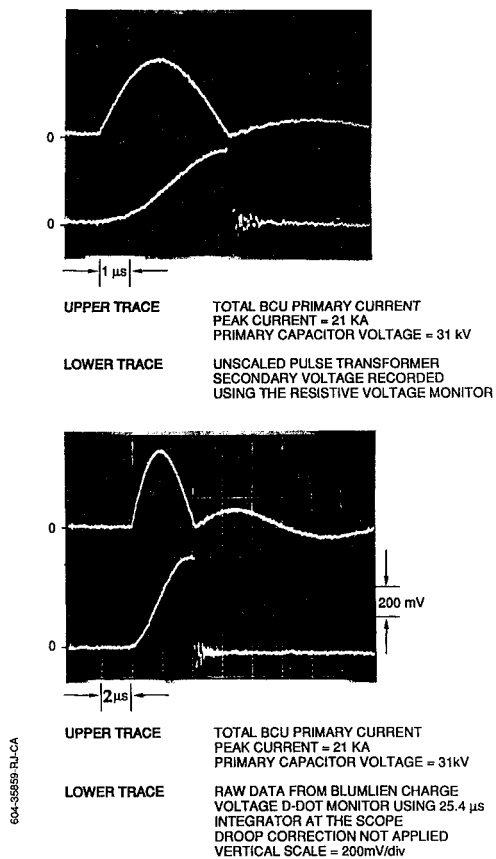
UPPER TRACE   TOTAL BCU PRIMARY CURRENT
PEAK CURRENT = 21 KA
PRIMARY CAPACITOR VOLTAGE = 31 kV

LOWER TRACE   UNSCALED PULSE TRANSFORMER
SECONDARY VOLTAGE RECORDED
USING THE RESISTIVE VOLTAGE MONITOR

UPPER TRACE   TOTAL BCU PRIMARY CURRENT
PEAK CURRENT = 21 KA
PRIMARY CAPACITOR VOLTAGE = 31kV

LOWER TRACE   RAW DATA FROM BLUMLIEN CHARGE
VOLTAGE D-DOT MONITOR USING 25.4 μs
INTEGRATOR AT THE SCOPE
DROOP CORRECTION NOT APPLIED
VERTICAL SCALE = 200mV/div

604-35859-RJ-CA

Figure 6.   Primary current and charging voltage.
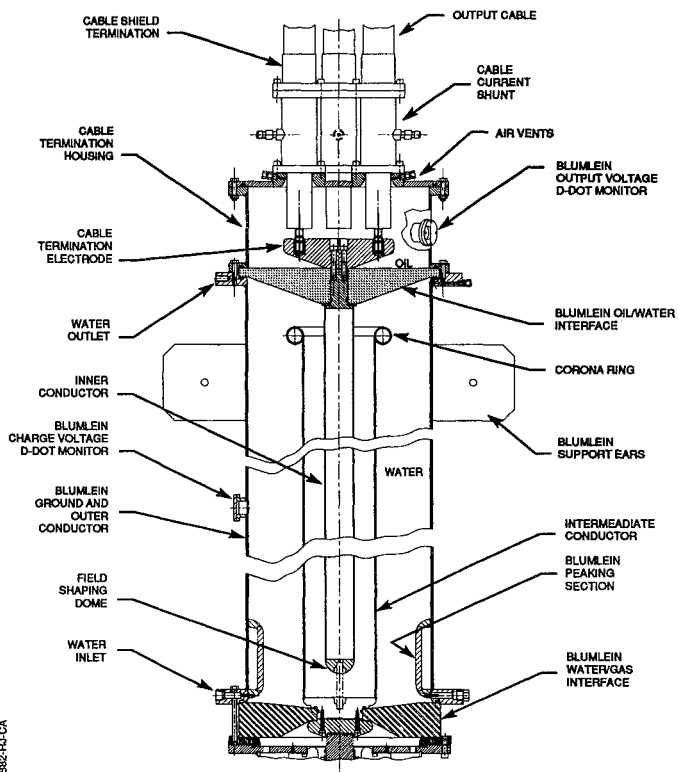

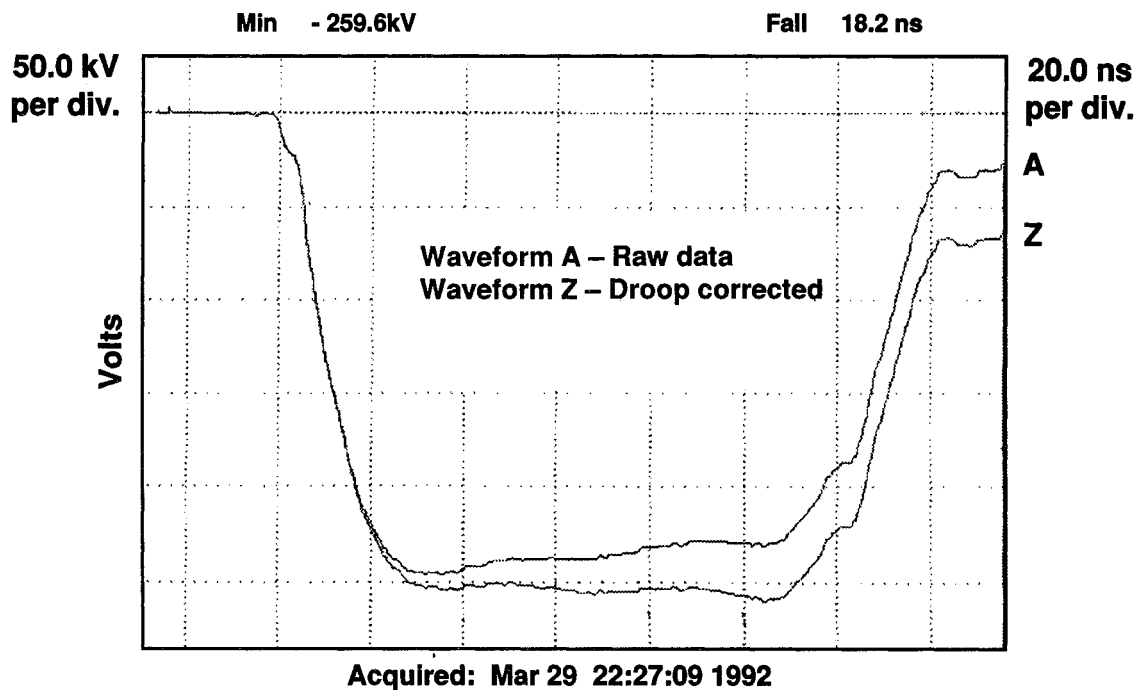604-35882-RJ-CA

Figure 7.   Blumlein cross section.

Figure 8.   Blumlein output pulse into matched load.

1418

stress ratio of ≤0.35 was used for all surfaces/mediums to ensure no more than 1 failure in >10^6 shots for the four Blumleins. Limiting to this ratio of 0.35 or less and a 5 µs charging time ($t_{ef} = 2.08$ µs), a 16 inch nominal diameter outer cylinder Blumlein was selected.

The inner cylinder in the Blumlein has the highest electrical stress and attains a negative polarity when switched. Consideration of the breakdown characteristics of this inner cylinder is most important since the intermediate cylinder has lower stresses due to larger radius of curvature. However, the larger radius makes the area substantially larger than that of the inner cylinder, which tends to lower the breakdown field associated with the intermediate cylinder. Also, the intermediate cylinder is charged positively, which reduces its breakdown field due to polarity effect. The breakdown probability depends on the ratio of the operating surface field strength to the breakdown field strength.

Maximum stress (~ 128 kV/cm) occurs at the rounded field shaping dome of the inner cylinder (toward the switch end) before the switch is triggered. The maximum operating stress on the intermediate cylinder during charging is 80 kV/cm which occurs at the cylinder open end corona ring. Following Blumlein switching the maximum field is present on the negatively charged output cable terminating electrode. The insulating interface, the intermediate cylinder corona ring, and the cable terminating electrode itself were shaped such that the maximum field (~ 90 kV/cm) was on this electrode in the transformer oil region. Breakdown strength of oil for these time scales is >500 kV/cm. The field stresses on the water side of the Rexolite interfaces of the Blumlein were very modest (~ 35 kV/cm). To date all four Blumleins have operated very reliably with no breakdowns.

Blumlein Switch Design: The BCU output is connected to the intermediate cylinder of the Blumlein via a coaxial switch located between the BCU and Blumlein. A cross section view of the Blumlein switch is shown in Figure 3-9. The switch is a cylindrically symmetric, three-electrode, SF_6 insulated spark gap. The trigger electrode consists of a thin walled tubular trigger electrode geometrically positioned midway between the main switch electrodes which are spaced ~ 1.4 cm apart. The switch trigger electrode, biased 55/45 percent, is triggered via a fast trigger pulse (rate-of-rise >10 kV/ns) applied via a 190 pF blocking capacitor and 50 Ω resistor in series, as shown in Figure 4.

The switch SF_6 operating pressure as a function of charge voltage is shown in Figure 3-10. The switch operates very reliably with an "m" factor (ratio of self-break to operating voltage) of m = 1.3 and a gas flow rate of 500 cc/min. Concentricity of the trigger electrode within the main electrode gap increases the likelihood of multiple arc channels, and is essential for uniform erosion of the switch electrodes and long life.

A number of important factors were considered in arriving at the proposed switch design. Conservative design principles were utilized while minimizing switch inductance to ensure fast risetime. The output pulse risetime is determined by the impedance of the outer half of the Blumlein (Z) along with switch inductance contributed by: (a) the distributed inductance contained in the transmission line elements which comprise the Blumlein switch, (b) the resistive phase of the spark in the switch, and (c) arc channel inductance. The effects of each of these factors must be accounted for to obtain a reasonable estimate of the ultimate pulse risetime.

The geometrical inductance for the switch was estimated by dividing the switch into distinct transmission line elements. These regions were as follows: (1) inductance L_1 due to the region between the spark gap and the conical throat of the switch, (2) inductance L_2 due to the conical transition of the switch, and (3) inductance L_3 contributed by the switch/Blumlein insulator. The net geometric inductance is $L_T = L_1 + L_2 + L_3$. This value was estimated to be 30 nH for the switch.

The switch inductance ($L(r)$) associated with the resistive phase of the arc can be estimated from the resistive phase risetime (τ) in sparks governed by the well known J.C. Martin empirical expression :

$$\tau = \frac{88 \left(\dfrac{\rho}{\rho o} \right)^{0.5}}{E^{4/3} Z^{1/3}} \, ns \qquad \text{Eq. 5}$$

or,

$$L(r) = \tau Z \qquad \text{Eq. 6}$$

where $(\rho/\rho o)$ is the ratio of the switch gas density to the density of air at atmospheric pressure, E is the switch operating field in units of 10 kV/cm, and Z is the impedance being driven by the switch. This inductance is on the order of 12 nH assuming a single arc channel in the switch.

In addition to the resistive phase, is the inductance of the arc channel itself. This value is well approximated as 15 nH/cm over the length of a single channel arc. For electrode spacing of ~1.4 cm, this contribution to the switch inductance is 21 nH. Thus, the estimated total switch inductance is ~63 nH . Hence, the output pulse risetime from the relationship

$$\tau_{rise} \approx \frac{2.2L}{Z}$$

Eq. 7

for Z = 6 Ω, is estimated to be ~23 ns. The value compares reasonably with the measured pulse risetime of 18 ns.
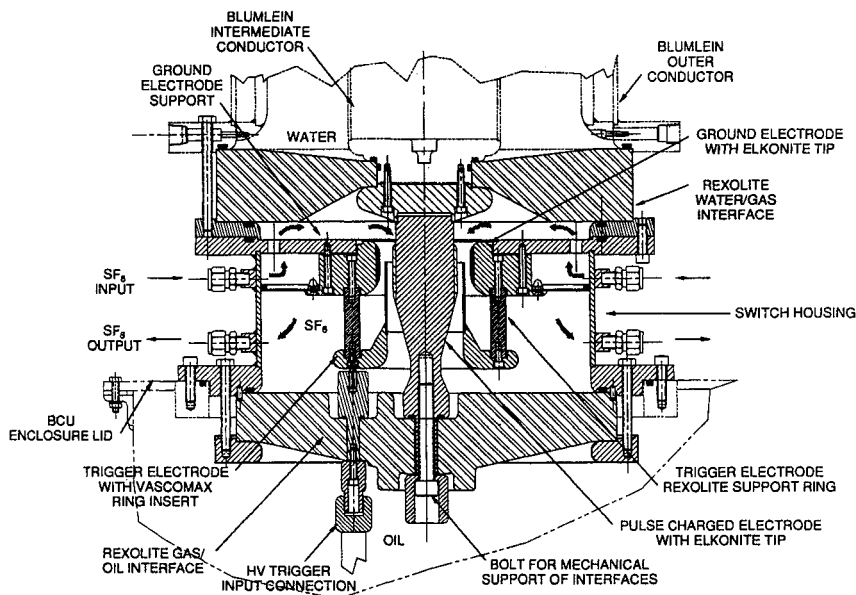

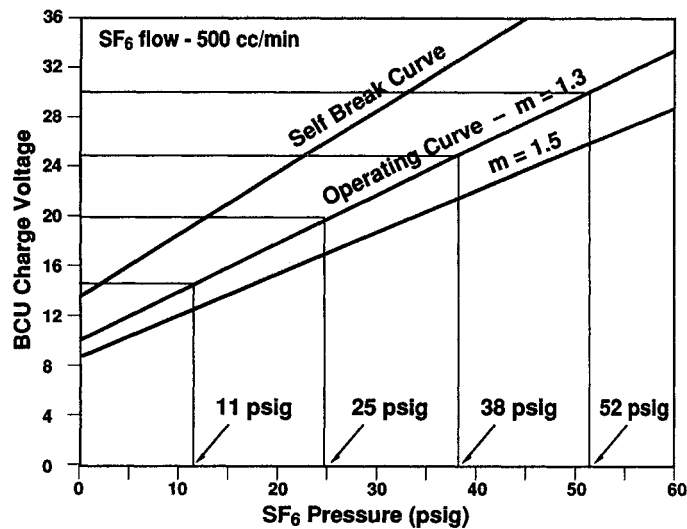Figure 9.   Cross section view of Blumlein switch.

Figure 10.   Blumlein switch SF$_6$ operating pressure (m = 1.3) curve.

Another main consideration in the switch design process was the high voltage integrity of the switch. To prevent surface flashovers, the switch was designed to minimize direct UV illumination of the insulator surfaces. UV illumination can greatly reduce the hold-off characteristics of insulators. In addition, the switch gas flow was carefully designed to minimize arc debris settling on the insulators.

The insulator and conductor geometry's were optimized to maintain uniform grading on the insulator surface. At full charge, the highest fields occur at the two edges of the uniform gap with fields of 225 kV/cm. The field in the gap area next to the trigger electrode (where the arc occurs) is 210 kV/cm on the positive (inner) electrode and 190 kV/cm on the outer electrode, so that the field variation along the central electrode is limited to 8% with the maximum field equal to 225 kV/cm. The switch sections most vulnerable to breakdown are the Rexolite insulator interfaces on either end of the switch. The peak field along the insulator-gas interface on the BCU side of the Blumlein switch was found to be + 100 kV/cm. This field value is low enough to assure a very low breakdown probability for the operating pressure of the switch. The Blumlein side of the switch Rexolite interface was shaped at a small angle on the gas side to reduce the stresses along the gas insulator interface. The highest stress point on the insulator is close to the triple point and the field is 70 kV/cm, which is again a very safe value. The maximum electric field on the oil side of the Blumlein switch interface occurs on the innermost electrode surface. The maximum field from the plots is found to be 73 kV/cm. Care is taken by appropriately shaping the electrode-interface junction such that the region of this peak field is located at points distant from the oil-insulator interface itself.

The midplane is the dominant component that controls the spark gap's tendency, or lack of it, to prefire or no-fire. Therefore, the midplane is carefully balanced so that it maintains its correct potential between the high voltage electrode and the ground electrode. If this is done with high precision, there is negligible field enhancement even though the edge of the trigger electrode is relatively sharp. The trigger electrode is electrostatically balanced with a resistive divider so that it maintains the proper balance potential, and is allowed to deviate from this value by less than 5%. The midplane itself is approximately capacitively balanced due to the stray capacitance between it and the main electrodes. However, it must be resistively balanced because the midplane is connected to the input trigger cable via a 50 Ω resistor and a 190 pF coupling capacitor. Without balancing resistors, the coupling capacitor would hold the midplane at ground during the charging cycle, thereby self-firing the gap. The balancing resistors must be sufficiently low in value to force the midplane to maintain balance potential despite the action of the coupling capacitor.

The figure of merit for the biasing resistor chain (effective resistance being parallel resistance of the two resistance arms of the divider) and the coupling capacitor is the RC product which should be at most one-tenth or less than the charging time. This RC time constant was ~25 times less than the Blumlein charging time which negligibly perturbs the trigger biasing potential during the Blumlein pulse charging. From system efficiency considerations, the balancing resistor values should not be set too low since it creates a loss mechanism which reduces the charge voltage on the Blumlein for a given primary capacitor voltage.

The four Blumlein switches have been in routine operation for well over 3 years and have required no maintenance. Initially a few of the bolts within the switch came loose. This problem was rectified by securing the bolts in place with a thread sealant. The spark gap conduction delay at 250 kV output was ~ 150 ns with jitter of ≤1 ns (1-sigma) and a total spread of <5 ns. The switch jitter increased somewhat at lower output voltage (125 kV) to ≤ 1.25 ns. Decreasing the trigger voltage from 200 kV to 100 kV had only a minor effect on switch performance. The switch jitter increased only minimally and remained of the same order as above.

CONCLUSION

The DARHT Induction Cell Pulsed Power Supply prototype system exceeded all design goals and specifications. As demonstrated by extensive testing at Maxwell followed with over three years of operation at Los Alamos National Laboratory, this design has proven its, cost effectiveness, reliability, and superior performance. This justifies its use as a very reliable power supply for Linear Induction Accelerator application.

REFERENCE

[1] "A 200 kV, Fast Risetime, Low Jitter Trigger System with Magnetic Pulse Sharpener", Twentieth Power Modulator Symposium, pp.227-233, (1992).